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ABSTRACT

An acoustically transparent, medium-power, bidirectional sound source has been designed and built for use in the USRD Anechoic Tank Facility at frequencies from 0.4 to 10 kHz, hydrostatic pressures from 0 to 1000 psig, and temperatures between 3 and 30°C. It consists of a planar 6x6 array of PZT-4 elements; the over-all dimensions are 19.5 in. wide, 26 in. long, and 1.5 in. thick. The transmitting current response is about 46 dB re 1 μbar/A at 0.4 kHz and rises 6 dB per octave to about 73 dB at 10 kHz. The output is linear with driving voltage to 200 V (rms). The transducer also can be used as a hydrophone; the free-field voltage sensitivity is about -100 dB re 1 V/μbar at frequencies from 1 Hz to 10 kHz.

PROBLEM STATUS

This is an interim report on the problem.

PROBLEM AUTHORIZATION

NRL PROBLEM S02-31

Project RF 05-111-401-4472

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CONTENTS

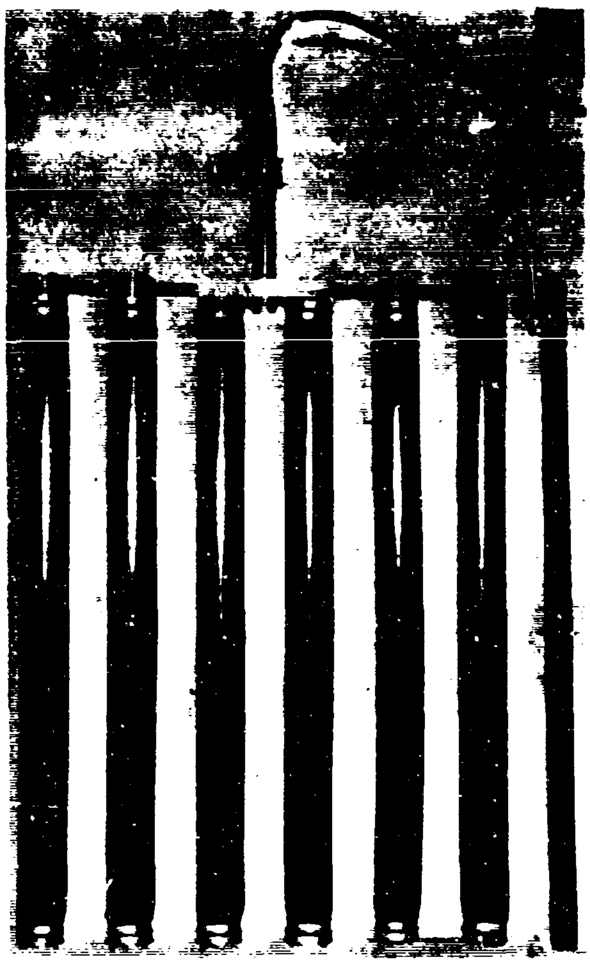
ILLUSTRATIONS

HIGH-PRESSURE PIEZOELECTRIC CERAMIC TRANSDUCER USRD TYPE F43

INTRODUCTION

The evaluation of developmental sonar transducers in the Underwater Sound Reference Division (USRD) Anechoic Tank Facility (ATF) frequently requires a sound source large enough to have good directional characteristics and powerful enough to produce higher acoustic output than can be obtained from most types of calibration transducers. An additional requirement is that the transducer be acoustically as transparent as possible to reduce the formation of standing waves between the sound source and the transducer being evaluated.

Transducers are calibrated in the ATF at hydrostatic pressures as high as 1000 psi and at temperatures from 3 to 30°C. A sound source that has stable electroacoustic characteristics within these ranges is particularly desirable in calibration work. One that meets these requirements has been designed and constructed by the Underwater Sound Reference Division.



Thirty-six piezoelectric elements constitute a plane-array sound source 19.5 in. wide, 26 in. long, and 1.5 in. thick, over all. The width has been made less than the 20-in.-dia port opening on the ATF pressure vessel to allow insertion and removal of the array. A photograph of the complete transducer is shown in Fig. 1.

Fig. 1. USRD type F43 capped-ceramic-element transducer.

CONSTRUCTION FEATURES

The F43 array consists of six identical line transducers mounted side by side on 3.5-in. centers. Each line consists of six 0.75-in.-dia by 0.75-in.-long radially polarized PZT-4 tubes with 0.062-in.-thick walls, mounted on 4-in. centers. This arrangement provides adequate support for the wave front to produce good directional characteristics to 12 kHz. Magnesium end caps cemented to the ceramic tubes with Epon VI epoxy shield the inner surfaces from the sound field. Elements constructed in this manner have good sensitivity [1] and are stable with high temperature and pressure, as has been verified by measurements on the USRD types F36, F37, and H33 transducers over a four-year period. Although air-filled capped ceramic tubes are subject to a two-dimensional stress, calibration measurements made at the USRD and by other investigators [2], [3] show little change in characteristics for PZT-4 material at pressures below 1000 psi.*

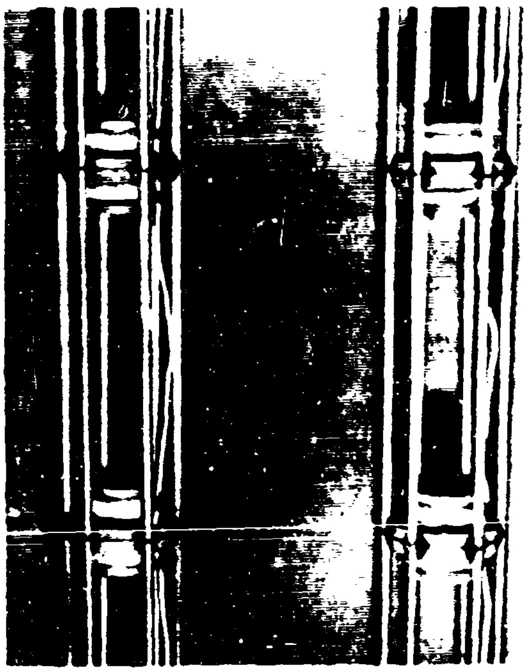


Fig. 2. Ceramic elements mounted on resilient rubber rings.

As shown in Fig. 2, the piezoelectric elements are mounted in resilient rings of natural rubber. A six-wire "birdcage" frame of 1/8-in.-dia steel rods provides the structural strength and support for the elements. The main design features can be seen in Fig. 3.** All elements are

*With some sacrifice in sensitivity [4], the capability for use at much higher pressure can be obtained by using a liquid-filled, end-capped ceramic element.

**Detailed construction drawings have been made for the F43 transducer. A complete list of the drawing numbers is provided on USRD drawing DM2528.

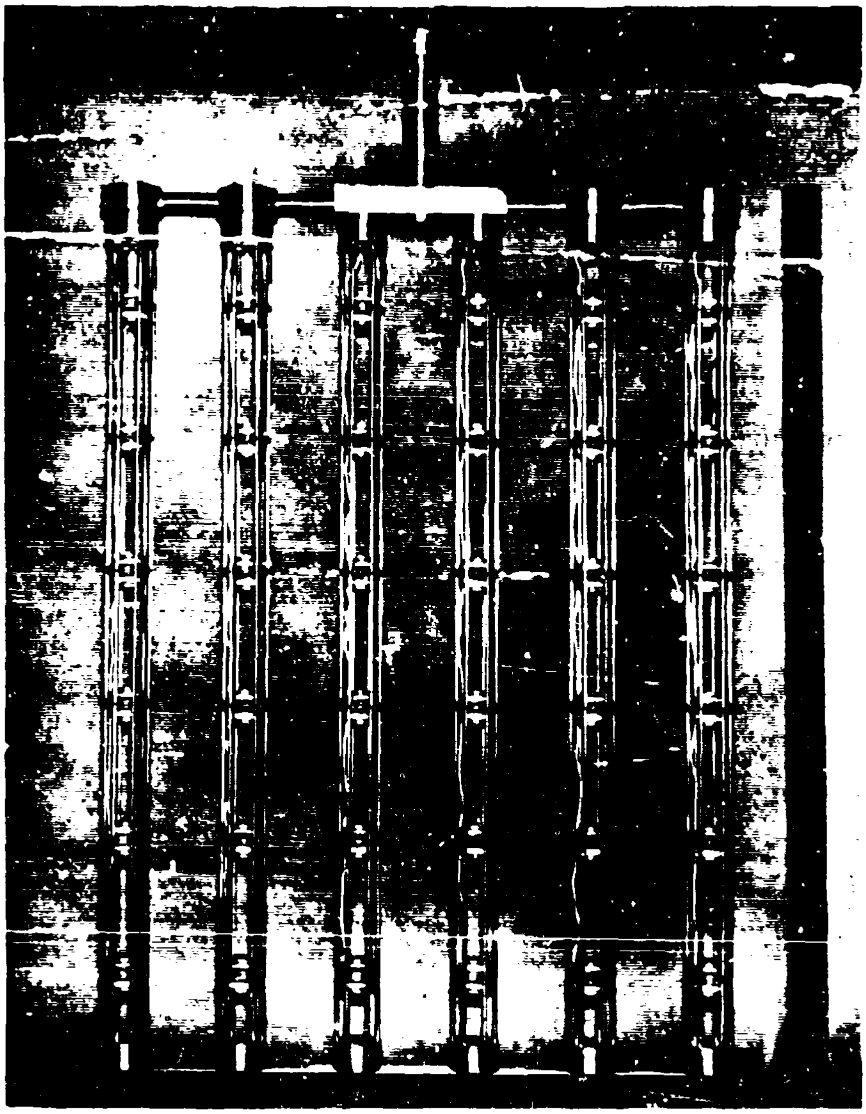


Fig. 3. Internal construction, type F43 transducer.

connected electrically in parallel; no shading is used in the vertical (XZ) plane, but the individual lines can be shaded in the horizontal (XY) plane.

A six-port manifold of stainless steel provides access for the electrical connections to each line and serves at the same time as the mechanical support for the array. A small tubular junction box can be added to house capacitors, which are inserted in series with four of the lines to provide shading in the horizontal plane when additional minor-lobe

suppression is required. Directivity patterns obtained with 3 steps of shading (coefficients 0.3, 0.7, 1.0, 1.0, 0.7, 0.3) are shown in Fig. 4. A wide choice of directional characteristics is available by selecting the shading coefficients.

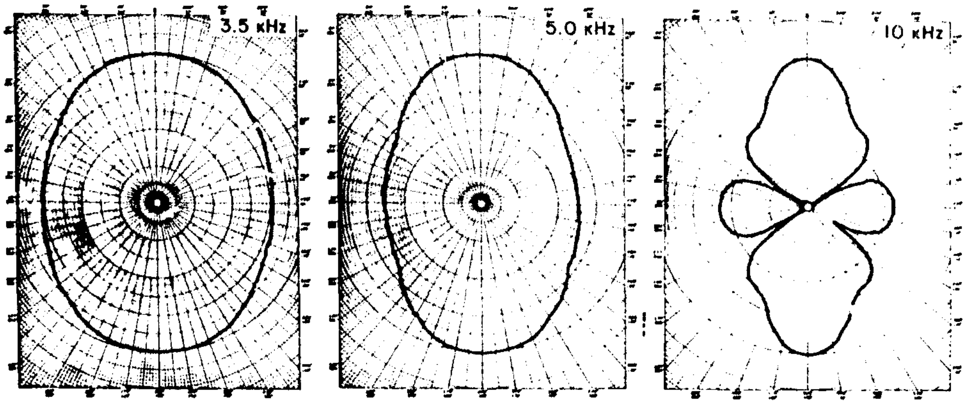


Fig. 4. Directivity patterns in the XY plane, type F43 transducer; shaded array.

The water permeability [5] of the butyl rubber compound used for the external covering of each line is less than 1/10 that of natural rubber, neoprene, or polyurethane compounds. The free sulfur content (as determined by the methods of ASTM D297-61T) of all elastomers used in the construction of the transducer is less than 0.1%. Tests made at the USRD have shown that elastomers containing a higher percentage of free sulfur after vulcanization cause the silver electrodes on the ceramic elements to turn gray or black, and ultimately cause premature failure of the transducer because of lowered capacitance or breakage of embrittled connecting wires. This effect can be especially severe at solder joints and at sharp bends in the wire. The transducer is filled with thoroughly dried and degassed Baker's DB grade castor oil.

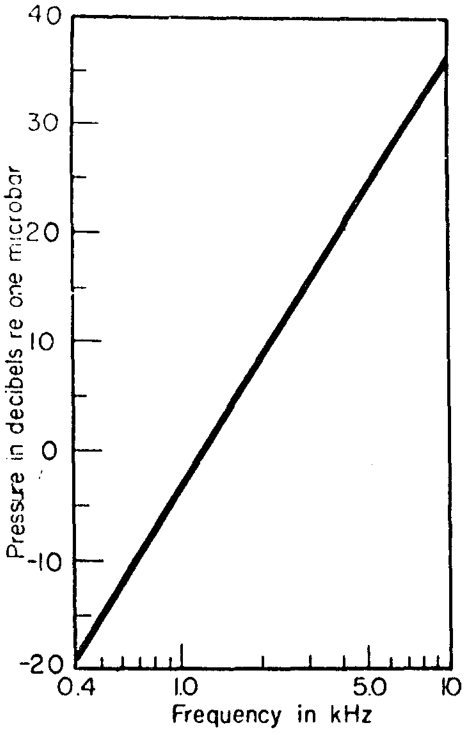
OPERATING CHARACTERISTICS

General Features

The type F43 transducer is a bidirectional, acoustically transparent, medium-power sound source for the frequency range 0.4 to 10 kHz. It can be used as a hydrophone to frequencies as low as 1 Hz. The transmitting voltage and current responses and the free-field voltage sensitivity are shown in Figs. 5, 6, and 7.

Directivity

Directivity patterns in the horizontal (XY) plane at the frequencies 1.0, 3.5, 5.0, and 10 kHz are shown in Fig. 8. The measured patterns



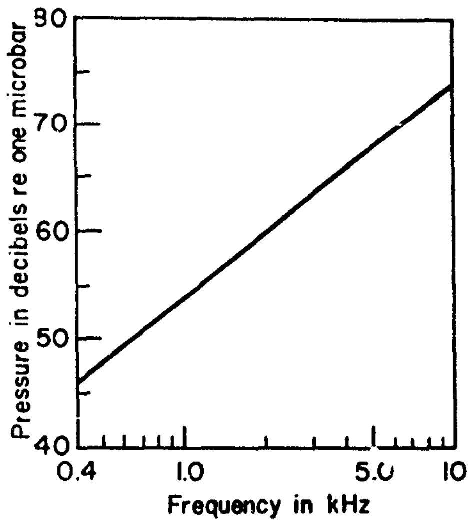
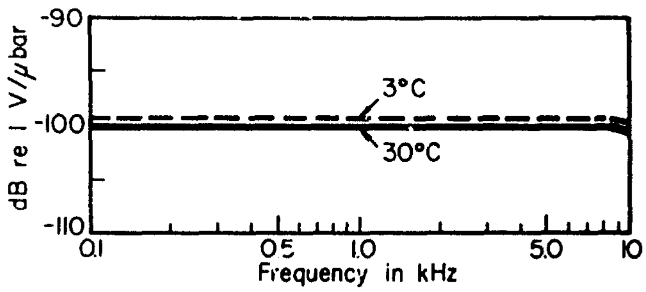


Fig. 6. Transmitting current response, type F43 transducer; pressure at one meter per ampere measured at end of 41-ft cable.

Fig. 5. Transmitting voltage response, type F43 transducer; pressure at one meter per volt applied at end of 41-ft cable.

Fig. 7. (right) Free-field voltage sensitivity at hydrostatic pressures to 1000 psig, type F43 transducer; open-circuit voltage at end of 41-ft cable.



agree well with theory. The first minor lobe is down by 13.5 dB. The effective width of 6 point sources of equal strength and phase is 21.0 in., which is the equivalent of a horizontal line of 6 segments, each 3.5 inches or one spacing wide. This can be seen readily from the equations of Appendix A.

Temperature Effects

Directivity patterns, free-field voltage sensitivity, and transmitting voltage response have been measured at 3, 10, and 30°C. The only measurable change in characteristics was a 0.5-dB increase in sensitivity

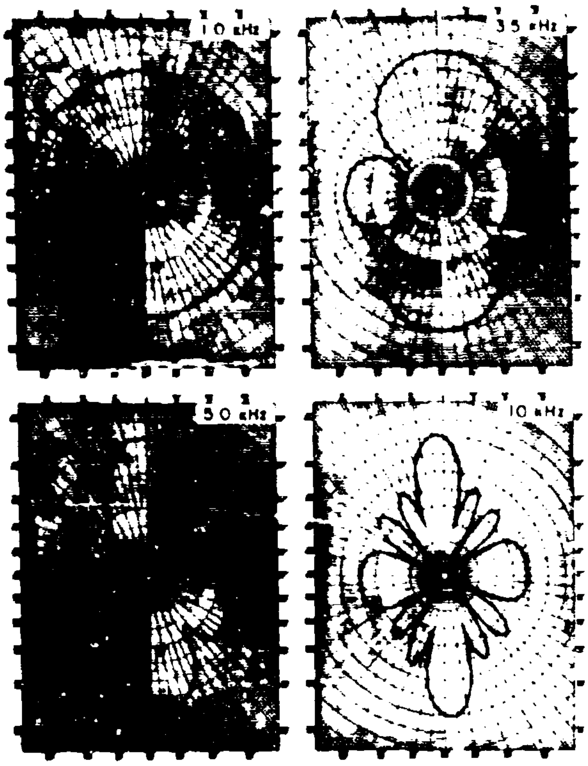


Fig. 8. Directivity patterns in the XY plane, type FZ3 transducer; unshaded array.

and response as the temperature was lowered from 30 to 3°C. This change is not permanent, but occurs each time the array is temperature cycled.

Hydrostatic Pressure Effects

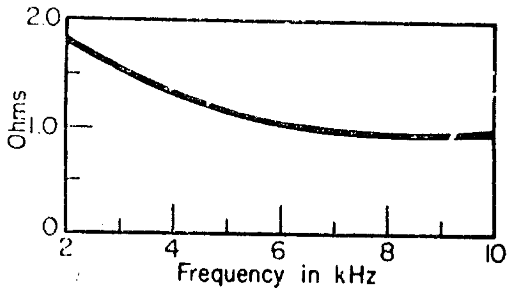
The acoustic characteristics with respect to pressure were determined from measurements in the ATF. They do not change in the pressure range 0 to 1000 psig at frequencies from 2 to 10 kHz. No measurable change in sensitivity has occurred after 12 months of use at temperatures between 3 and 30°C, and after more than 150 pressure cycles from 0 to 1000 psi.

Voltage Linearity

The output of the transducer is linear with driving voltages to 200 V (rms). This value is well below the a-c depoling voltage for PZT-4, and heating caused by dielectric loss is negligible.

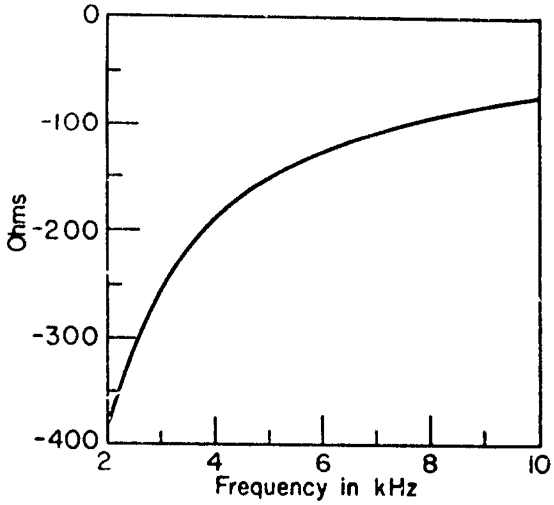
Impedance

Impedance values measured at the temperature 10°C and the pressures 0 and 1000 psi are shown in Fig. 9 (a), (b), and (c). Hydrostatic pressure to 1000 psi does not cause any significant impedance change.



a. (above) Resistance.

b. (right) Reactance.



c. Impedance magnitude.

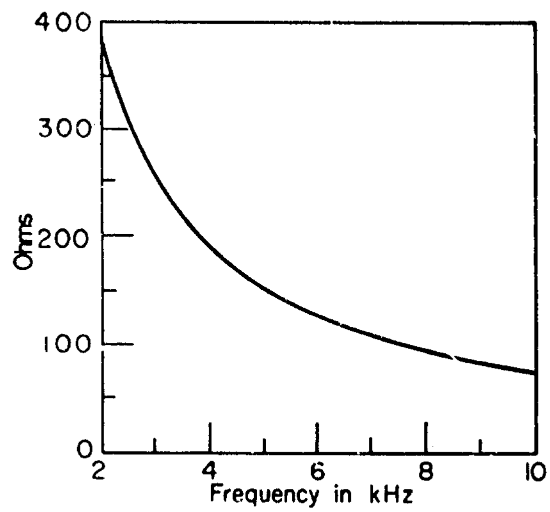


Fig. 9. Impedance characteristics, type F43 transducer.

CONCLUSION

The USRD type F43 transducer is a pressure- and temperature-stable array suitable for use to 1000 psi. The design features can be used in other applications, such as near-field arrays and submarine-mounted hydrophone systems.

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[1] R. A. Langevin, "The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes," J. Acoust. Soc. Am. 26, 421-427 (1954).

[2] R. F. Brown, "Environmental Effects on the Properties of Piezoelectric Ceramics," JUA(USN) 15, 284-289 (1965).

[3] R. F. Brown, "Effect of Two-Dimensional Mechanical Stress on the Dielectric Properties of Ceramic Barium Titanate and Lead Zirconate Titanate," Naval Research Establishment (Canada) Report 60/5, Sep 1960.

[4] G. W. McMahon, "Sensitivity of Liquid-Filled, End-Capped, Cylindrical, Ceramic Hydrophones," J. Acoust. Soc. Am. 36, 695-696 (1964).

[5] A. Lebovits, "The Permeability of Hydrophone Boot Materials, Encapsulants, and Various Other Materials to Water at Ambient and High Hydrostatic Pressure," Lab Project IED-7 Progress Report No. 1-ZF 020-98-01 (DDC No. 828-818L), U. S. Naval Applied Science Laboratory, Brooklyn, N. Y., 1 Mar 1968.

Appendix A

EFFECTIVE WIDTH OF THE TRANSDUCER

The general expression for the pressure p in the far field of a source, in the direction θ, produced by a line of m uniform points with separations d is

$$p_\theta = (1/m) \sum_{n=1}^{m} e^{-jk(n-1)d \sin\theta} \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number. The summation of Eq. (1) can be given as

$$p_\theta = \frac{\sin(\frac{1}{2}mkd \sin\theta)}{m \sin(\frac{1}{2}kd \sin\theta)} . \tag{2}$$

If we let $m \to \infty$ and $d \to 0$ in such a manner that the product md remains constant, the effect of the line of points approaches that of a continuous line. The approximation $\sin x \approx x$ can be used in the denominator of Eq. (2) to obtain

$$p_\theta = \frac{\sin(\frac{1}{2}kL \sin\theta)}{\frac{1}{2}kL \sin\theta} \tag{3}$$

where $L = md$. The effective length L of a line of many closely spaced points is md, although the distance between the end points is $(m - 1)d$.

For the F43 transducer, $m = 6$ and $d = 3.5$ in.; the effective length L, or, in this case, width, is, therefore, 21.0 in. The computed values using 21.0 in. are in good agreement with the measured directivity patterns for the unshaded array.

Appendix B

CALCULATION OF SENSITIVITY

The free-field voltage sensitivity for the capped piezoelectric ceramic element can be computed from the relation

$$V/p_0 = b\left[g_{33}\left(\frac{1-\rho}{1+\rho}\right) + g_{31}\left(\frac{2+\rho}{1+\rho}\right)\right], \tag{1}$$

as adapted from Eq. (12), reference [1], where V is the open-circuit output voltage developed by the element, a and b are the inner and outer radii, respectively, of the ceramic tube, in meters; g_{33} and g_{31} are the electromechanical voltage constants of the ceramic material, $\rho = a/b$ = ratio of the inner to the outer radius, and p_0 is the external pressure in newtons/meter^2.

Nominal values for the electromechanical voltage constants of PZT-4 are:

$$g_{33} = 24.0\times10^{-3}\ \mathrm{Vm^{-1}/Nm^{-2}}$$

$$g_{31} = -10.4\times10^{-3}\ \mathrm{Vm^{-1}/Nm^{-2}}$$

Dimensions of the ceramic element in the F43 transducer are:

outer radius b = 0.375 in. (9.52×10^{-3} m)

inner radius a = 0.313 in. (7.95×10^{-3} m)

$\rho = 0.835$

Substituting $p_0 = 1$ dyne/cm^2 (10^{-1} N/m^2) in Eq. (1), yields

$$V = 13.2\times10^{-6}\ \mathrm{V/\mu bar},$$

which is the free-field voltage sensitivity M_0 of the element when the dimensions are small in comparison with the wavelength. Expressed in dB re 1 V/μbar, $M_0 = 20 \log 13.2\times10^{-6} = -97.6$ dB.

The sensitivity of the F43 transducer measured at the end of a 40-ft cable is -99.5 dB re 1 V/μbar. The shunt capacitance of the cable is less than 0.1% of the capacitance of the total array, and thus has negligible effect on the sensitivity.

Test were made on three 3/4x3/4x1/16-in. wall thickness ceramic tubes to determine the loss in sensitivity resulting from the clamping effect of the end caps when they were cemented with rigid epoxy cement. It was found that the sensitivity was reduced, on the average, by 1.5 dB from the value that resulted when a compliant rubber-base cement was used.

A reduction in sensitivity of the same magnitude was measured for the $\frac{1}{2}$x$\frac{1}{2}$x1/8-in. wall thickness ceramic tubes used in the construction of the near-field array. The computed sensitivity M_0 reduced by 1.5 dB gives the value -99.1 dB. Any other difference between measured and computed values can be attributed to measurement error or incorrect values of g_{33} and g_{31}.

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